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The Madsen Aurical

[1]Jane E. Baer, Ph.D. and [2]Jennifer Groth, M.A.

[1]Training & Technical Support Coordinator, Madsen Electronics, 5600 Rowland Road, Minnetonka, MN 55343 (currently with Starkey Labs, Inc.) and [2]Research Audiologist, GN Danavox, Copenhagen

INTRODUCTION

As technological advances increase at a rapid pace, so must the technological applications within the field of audiology. It is now possible to have a totally automated office system where patient data is stored in computers rather than paper files. The Madsen Aurical™ is designed to fit the clinical needs of today and the future! The Aurical, shown in Figure 1, is a compact hearing aid fitting system. The Aurical includes an audiometer, a real ear measurement system, a hearing instrument test box, and a HI-PRO programmer. All of these "pieces" of equipment are combined physically into one instrument, as well as being integrated within the computer so information is easily transferred between the measurement modules (i.e., the computer programs which drive the "pieces" of equipment). The audiologist controls the functions of the equipment by using the computer keyboard or mouse. This integration and simple transferring of information between modules is highly efficient. Using the Aurical system can thus reduce the time the audiologist spends evaluating the patient and his/her hearing aid, thereby, allowing more time for working with and counseling the patient, which will benefit everyone involved. The following pages will describe the Aurical and its specific modules in more detail.

THE AURICAL AUDIOMETER MODULE

The Aurical audiometer module can be divided into three sections, diagnostic audiometry (HL and speech testing), (re)habilitative audiometry (SPL testing), and loudness scaling. Each of these sections will be discussed individually.

Diagnostic Audiometry

The Aurical audiometer module includes many unique functions. It is important to realize, however, that in addition to these unique functions the Aurical is a "traditional" two-channel audiometer. With the Aurical, the audiologist can perform all standard and advanced audiometric procedures that are performed with a traditional audiometer, including air and bone conduction audiometry, speech audiometry, and central auditory testing. An example of the audiometry screen within the Aurical can be seen in Figure 2. From this computer screen the audiologist is able to change the stimulus signal and the routing of that signal using the three columns of icons in the center of the screen. By clicking on the desired icon(s) in the outside columns, the audiologist can select a signal that is a pure tone, pulsed tone, warble tone, narrow band noise, white noise, or speech weighted noise. The middle column of icons allows the audiologist to route the signal from each channel into the desired ear(s). The routing icons are abbreviated for the right ear [R], the left ear [L], or both ears [B]. Thresholds can be obtained in dB HL using either TDH or insert earphones. The type of transducer is selected via the icon bar across the top of the screen. Thresholds are entered onto the screen by clicking on the Store button, or simply pressing the "S" key. As thresholds are entered, the pure tone average (PTA) is calculated and displayed underneath the audiogram. The frequencies used to calculate the pure tone average are programmed by the Aurical user and can be easily changed if desired. In addition to plotting thresholds, MCL and UCL responses can be plotted by selecting them within the "Test" box in the bottom left of the screen. The Aurical

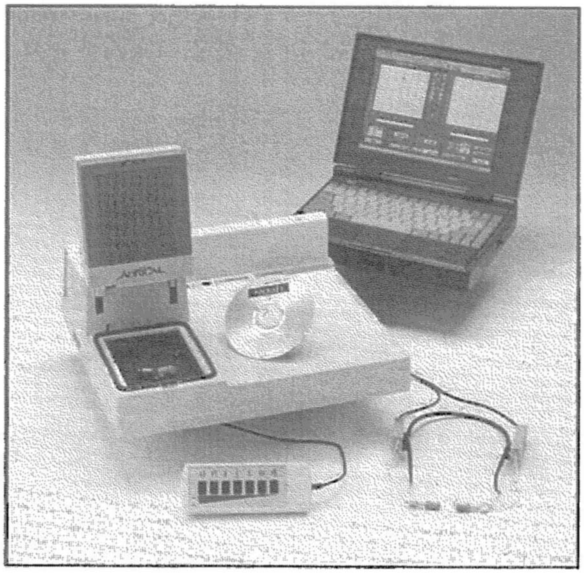

Figure 1: The Madsen Aurical™ is shown with a computer which is used to control the functions of the audiometer, loudness scaling testing, real ear measurement system, and hearing instrument test box, as well as other NOAH compatible programs.

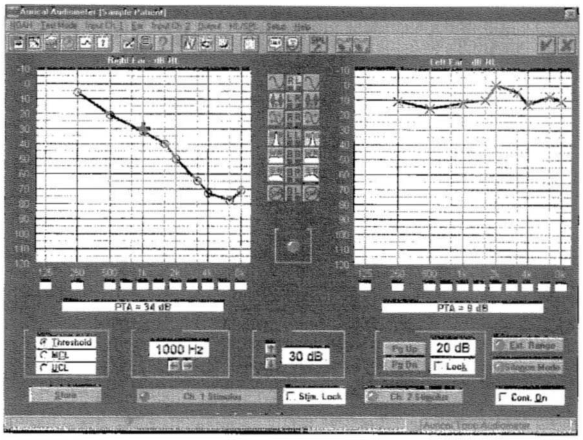

Figure 2: An audiogram obtained with the Aurical.

was originally designed to be a portable system which may be used with or without a sound booth, therefore, it incorporates a special feature called "Silence Mode". When "Silence Mode" is turned on it allows the Aurical user to present a stimulus by simply dragging the mouse over the "Ch. 1 Stimulus" button on the screen. Dragging the mouse over the button instead of clicking on the button or pressing the space bar reduces the unintentional cues that can be sent to the patient by moving one's hand to press the buttons or keys. All of these features can all be implemented easily and quickly via the keyboard or the mouse.

SPL Audiometry

In addition to traditional audiometric testing it is possible to perform SPL audiometry within the Aurical audiometry module. The concept behind performing audiometric testing in dB SPL, versus dB HL, is based on the premise that the results of the evaluation will be used to fit the patient with hearing aids. When working with hearing aids, most measurements of hearing aid performance are recorded in dB SPL (i.e., measurements made in the test box or using real ear measurement). If the audiometric information has been obtained in dB HL, conversions are required to transfer the information from dB HL to dB SPL. Threshold transfers from dB HL to dB SPL are based on the ISO 226 standard (1987) and the work of Shaw and Vaillancourt (1985). Since these conversions are based on average data, they may not accurately represent the SPL in the ear canal of an individual patient. A study by Valente and colleagues (1994) investigated the intersubject variability of the SPL measured near the eardrum when a 90 dB HL signal was presented via TDH-39 or ER-3A earphones. When the resulting SPL levels in individual ears were compared, the differences ranged from 9 to 36 dB, depending on the earphone and frequency. These wide ranges support the need for SPL audiometric testing in individuals who will be fit with hearing aids. By measuring hearing thresholds in SPL, intensity measurements are accurate for each individual ear and no conversion from HL to SPL is required. Measuring audiometric information in the same mode as other hearing aid measurements simplifies the hearing aid fitting process.

When using the Aurical to perform audiometric testing in dB SPL, the system uses a special headset. The headset, which is shown in Figure 1, easily calibrates the SPL level in the patient's ear canal. When testing a patient using the SPL headset, the audiologist simply places the insert phones in the patient's ear canals and initiates the calibration through a short series of mouse clicks. The calibration procedure is completed quickly and automatically through the SPL headset by presenting a pure tone at a known SPL level (70 dB SPL) then recording the exact SPL level in the patient's ear. The automated calibration quickly sweeps through the frequency range using this procedure. The calibration information is then

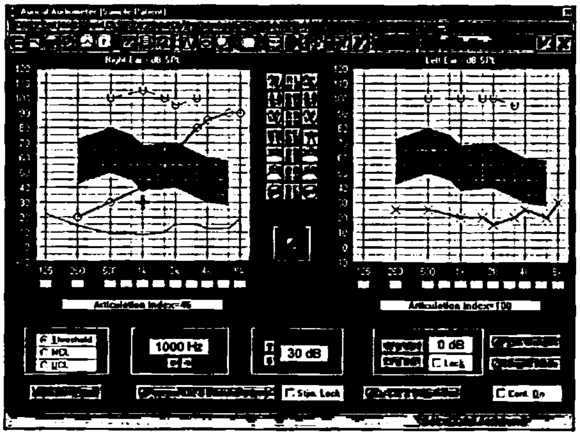

Figure 3: An SPL audiogram obtained with the Aurical.

stored in the Aurical and used during testing of that patient for that test session. Once the patient's specific calibration values have been recorded, the audiologist tests the patient's SPL thresholds using the same procedures as conventional audiometry. In addition to the calibration procedure, the headset uses insert earphones which attenuate background noise and, therefore, make it possible to test hearing outside of a soundbooth. This calibration process and testing procedure allows the audiologist to obtain ear specific SPL thresholds for the patient easily and accurately. Eliminating the normative conversion from HL to SPL also provides more patient specific real ear and coupler measurement targets for testing hearing aid performance. Using the targets and information generated by SPL testing should lead to a more accurate, and thus more successful hearing aid fitting. An example of the SPL audiometry screen is shown in Figure 3. Note that the SPL audiometry screen displays the average speech spectrum on the audiogram and figures the articulation index automatically according to the method outlined by Mueller and Killion (1990) and adapted to SPL (ISO 226, 1987; Shaw and Vaillancourt, 1985). The audiogram in Figure 3 displays both the threshold and UCL levels recorded in SPL for this patient. The audiogram for the right ear demonstrates severe recruitment, specifically in the high frequencies. This example will be continued through the next section on loudness scaling.

Loudness Scaling

The third component of the Aurical audiometry module is the ability to perform loudness scaling. Three loudness scaling protocols are pre-programmed into the Aurical audiometry module. These protocols are the Madsen/Kiessling procedure (Kiessling et al, 1996), the LGOB [Loudness Growth in Octave Bands] procedure (Pluvinage, 1989), and the IHAFF [Independent Hearing Aid Fitting Forum] procedure (Valente and Van Vliet, 1997). The basic parameters of each of the three pre-programmed loudness scaling protocols are shown in Table 1. Kiessling and colleagues (1996) compared the response consistency of the three loudness scaling protocols programmed into the Aurical. They found that the Madsen/Kiessling procedure and the IHAFF procedure were comparable and showed better response

Table 1. The basic parameters of the three loudness scaling protocols that are pre-programmed into the Aurical: the Madsen/Kiessling protocol; the LGOB protocol (Pluvinage, 1989); and the IHAFF protocol (Valente and Van Vliet, 1997).

Loudness Scaling Protocol	MADSEN/KIESSLING	LGOB	IHAFF
Stimulus	2 NBN bursts	3 NBN bursts	Pulsed Warble tones or NBN
Stimulus Presentation	Strategic randomization	Randomized	3 or 4 runs + 1 practice run
Loudness Judgments	Not Audible Very Soft Soft Comfortable Loud Very Loud Too Loud	Cannot Hear Very Soft Soft Comfortable Loud Very Loud Too Loud	Very Soft Soft Comfortable, but Soft Comfortable Comfortable, but Loud Loud Loud but OK Uncomfortable
Frequencies Tested	Audiologist's choice	500, 1k, 2k, 4k Hz	500 and 3k Hz + any others the audiologist selects

consistency than the LGOB. They also investigated the time required to perform each test protocol and found the Madsen/Kiessling procedure and the LGOB procedure to be comparable, while the IHAFF procedure required more time.

In addition to the three pre-programmed protocols, it is possible for the audiologist to program in his/her own loudness scaling protocol. Audiologists who choose to create their own loudness scaling protocol can select from the following stimulus options: single warble tone, double narrow band noise (NBN), double warble tones, double pure tones, triple NBN, or triple warble tones. Any of these protocols can be performed in either dB HL (using TDH-39 or ER-3A earphones or sound field speakers) or dB SPL (using the Madsen headset for SPL audiometry). The patient's responses during the test procedure are recorded via the Aurical response wand, which is shown in Figure 1. The ability to test in SPL gives the audiologist more accurate information about the exact SPL level at which the patient perceives sound as "soft", "comfortable", "too loud", and any loudness judgment in between. Since these responses are measured in SPL, normative conversion factors are not required for transferring the data into real ear target values. Loudness scaling results are used by the audiologist to obtain precise information about the patient's judgment of the loudness of sound at various frequencies and in each ear. The results of a loudness scaling test are shown in Figure 4. The loudness scaling results for the right ear are consistent with a high frequency sensory hearing loss, whereas the loudness scaling results for the left ear are consistent with normal hearing

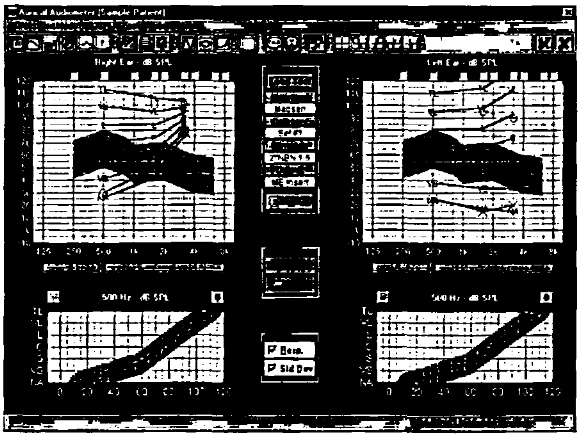

Figure 4: Results from an SPL loudness scaling test obtained with the Aurical.

sensitivity. The loudness scaling results of the hearing impaired ear (the right ear) show different ranges of loudness perception in different frequency ranges. As the patient's thresholds increase, the "Too Loud" response does not increase at the same rate. Therefore, the graph shows a reasonably wide range of loudness perception at 500 Hz (40 to 110 dB SPL between "very soft" and "too loud"), a slightly reduced range of loudness perception at 1500 Hz (50 to 105 dB SPL), and a severely reduced range of loudness perception at 3000 Hz (80 to 100 dB SPL). This pattern is consistent with recruitment, or abnormal growth of loudness, in the high frequencies. It is this variable loudness perception at different frequencies that must be addressed when fitting a hearing aid on a patient with this type of test result. Using this information to fit a nonlinear hearing aid helps the audiologist adjust the parameters of the instrument most appropriately for the patient's specific loudness perception.

In addition to using this information to better fit the hearing aids to the patient, the loudness scaling information can also be used for patient counseling. By zooming in on each section of the loudness scaling screen individually, the audiologist can use the graphs at the bottom to show the patient how his/her judgment of the loudness of sound changes depending on the frequency. The boxes marked "Resp" and "Std. Dev" allow the audiologist to display the average loudness scaling response of normal hearing individuals (i.e., the angled line in the middle of the gray range) and/or the range of one standard deviation around this average, respectively (Kiessling et al, 1996). Figures 5a, 5b, and 5c show the regression lines of the patient's responses (the straight lines) plotted against the responses of normal hearing individuals (the angled lines) for 500 Hz, 1500 Hz, and 3000 Hz, respectively. These graphs also show the patient's loudness judgment response to each stimulus, as each gray dot plotted on the graph represents an individual response. Showing the patient how their responses fit into the normal range at 500 Hz, but are well outside the normal hearing range for 3000 Hz, helps the patient to better understand the complicated process of fitting the hearing aid to their individual hearing loss. Understanding the complications involved may increase the patient's willingness to consider more advanced technology in order to better accomplish the goals of the hearing aid fitting. The audiologist also obtains better information about the patient's loudness judgments and, therefore, is

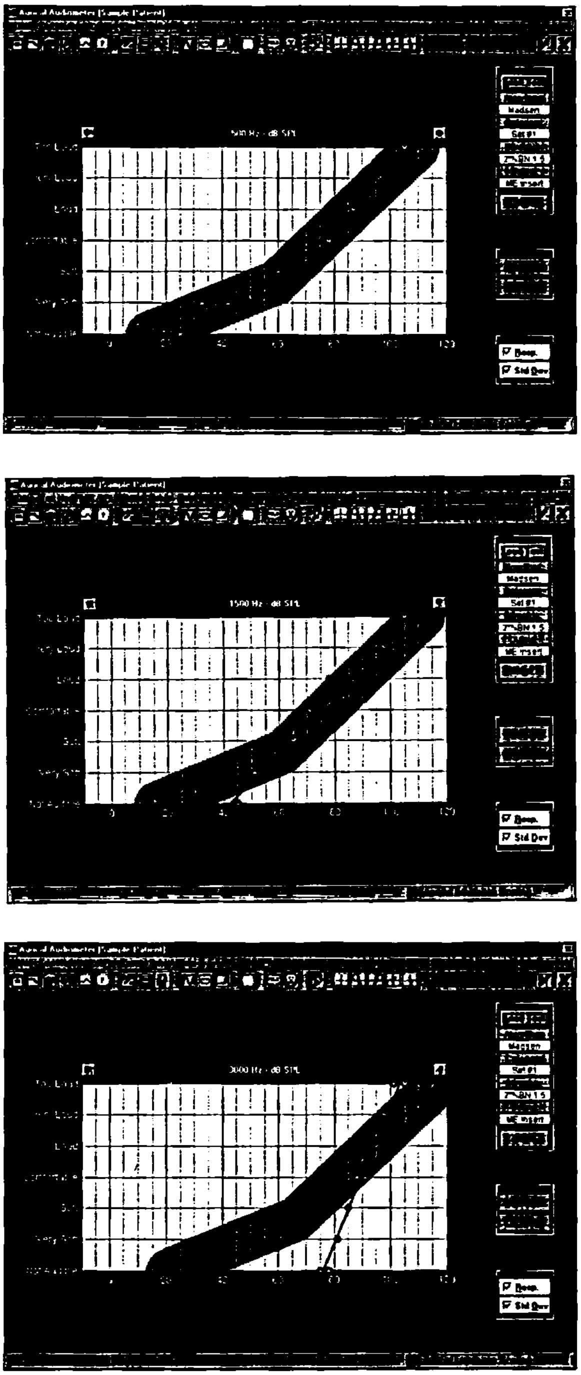

Figure 5: a) Patient specific loudness scaling response at 500 Hz; b) 1500 Hz; and c) 3000 Hz.

able to choose a more appropriate hearing aid and/or hearing aid program for the individual patient. If the patient demonstrates significant recruitment in certain frequency ranges and not in others, the audiologist can use this information to select the compression ratios, the threshold knee-points, and/or the crossover frequencies for the various frequency ranges. The value of this information is increased even more when the information is transferred into the real ear measurement module for verification of the hearing aid fitting. Thus, incorporating loudness scaling into a clinical practice offers multiple benefits to both the clinician and the patient.

THE REAL EAR MEASUREMENT MODULE

The transferring of information from the Aurical audiometer module to the Aurical real ear module is automatic. The transferred data is directly computed into a real ear measurement target which is based on whichever target formula the audiologist has selected within the software (possible pre-programmed target formulas include Berger, Bergerl, Berger2, Bynton, Danafit, Half Gain Rule, Libby, Loudness, NAL [1976], NAL-R [1986], NAL-RP [1989], POGO1, POGO2, and Third Gain Rule). The audiologist also has the option of selecting the "binaural enabled" function within the Aurical. If this option is selected, the binaural correction appropriate for the selected target formula will be applied to the real ear target. In addition to pre-programmed real ear target rules, the audiologist can program in his/her own target formula if desired.

The Aurical real ear screen displays two graphs, the real ear gain and the real ear output (insitu SPL). These screens are typically displayed with the real ear gain screen being larger, however, they can be reversed if the audiologist prefers to look at the real ear output. The real ear target is displayed on the real ear gain graph, while the real ear output graph shows the audiogram in SPL (either measured or converted) and the measured or predicted UCLs which set the output limit for real ear measurement. If frequency specific UCLs are not measured, the UCL's will be predicted based on research by Pascoe (1988). The audiologist can easily record the desired test by clicking on the appropriate button: Tube Cal [for performing the tube calibration], REUR [real ear unaided response], REOR [real ear occluded response], or REIR [real ear insertion response] (Schweitzer et al, 1990) and is able to change parameters easily by clicking on the icons on the menu bar (refer to Figures 6 and 7). Also shown in Figures 6 and 7 are the Target and UCL buttons. By clicking on the Target button, the audiologist is able to easily change the selected formula

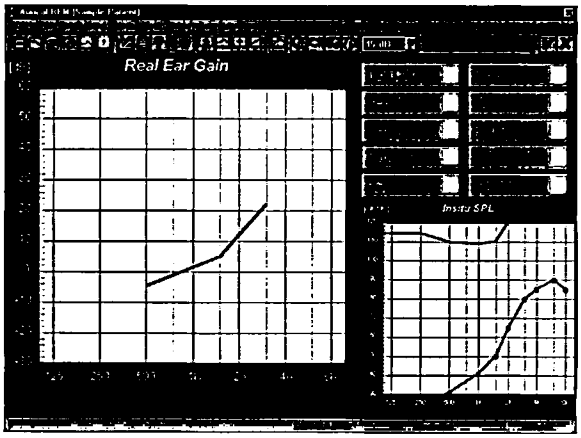

Figure 6: A real ear measurement target derived from the patient's loudness scaling responses for a 45 dB input signal.

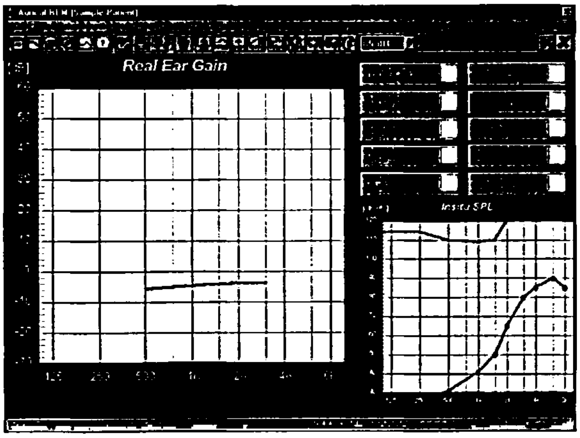

Figure 7: A real ear measurement target derived from the patient's loudness scaling responses for an 85 dB input signal.

for the real ear gain target. The UCL button allows the audiologist to adjust the maximum output that the Aurical will measure in the patient's ear without automatically stopping the test. In selecting the real ear measurement stimulus the audiologist can choose a pure tone sweep, a randomized white noise, or a randomized speech weighted noise, and is able to manipulate the parameters of the stimulus to the desired settings.

The power of the instrument is shown when the audiometric data is collected in SPL. The targets generated are based on the patient's SPL thresholds and do not require any conversion from HL to SPL using normative data, therefore, the targets are more accurate than targets created using converted data. When the patient has undergone a loudness scaling test that data can also be used to create a real ear target. Again, when the loudness scaling procedure is done in SPL, it is not necessary to apply normative conversions from HL to SPL. Therefore, the real ear targets which are based on the patient's loudness judgments are more accurate. Examples of real ear targets based on the sample patient's right ear loudness judgments are shown in Figures 6 and 7. Figure 6 shows the real ear target for a 45 dB SPL input signal, whereas Figure 7 shows the real ear target for an 85 dB SPL input signal. The distinct difference between these two targets shows that the patient needs significantly more gain for a 45 dB SPL target (i.e., a soft sound), than for an 85 dB SPL target (i.e., a loud sound). The benefit of performing loudness scaling is that when that data is transferred to the real ear measurement module, it is possible to create targets for any input level based on the patient specific responses. These targets are created by comparing the loudness scaling response of the patient to the average loudness scaling response of normal hearing listeners (Kiessling et al, 1996). The appropriate amount of gain required for the patient to achieve a normal loudness scaling judgment is prescribed in the real ear target. These multiple targets can help the audiologist to use a "soft", a "comfortable", and a "loud" target to adjust the patient's nonlinear hearing aid to most appropriately approximate the various targets. In this way, nonlinear amplification can be used to its fullest potential to accomplish the goal of moving all sounds into the range of audibility without exceeding the patient's "Too Loud" (UCL) limit, as well as focusing the majority of speech sounds around the patient's comfortable target.

When comparing the use of loudness scaling targets to targets for hearing aids with linear signal processing, such as NAL-R (Byrne and Dillon, 1986), it is important to note that the target formulas for linear hearing aids do not offer variable targets for variable input levels. Figures 8 and 9 show the NAL-R targets for a 45 dB SPL input signal and an 85 dB SPL input signal, respectively. Note that the target is the same for both input signal levels. The target does not change, because it was not designed to change. NAL-R and other commonly used fitting formulas were developed for use with linear amplification, therefore, the hearing aid could only hit one target (a 65 dB input target). With nonlinear amplification and rapidly advancing hearing instrument technology, however, audiologists are able to manipu-

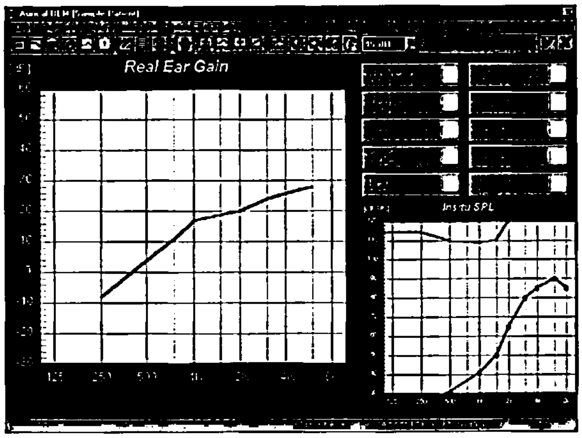

Figure 8: A real ear measurement target derived from the NAL-R formula for a 45 dB input signal.

late more parameters and better control the response of the hearing aids for more than one input level.

The Aurical real ear measurement system also has a feature which allows the audiologist to switch between the real ear measurement screen and the coupler by clicking an icon. This feature can be used for difficult-to-test patients who may not be able to sit through real ear testing procedures. When the coupler feature is selected, the real ear target is transferred into a coupler target. The transfer from a real ear target to a coupler target is made more accurately by allowing the audiologist to select which type of hearing aid is being fit on the patient. The microphone correction factors specific to the selected hearing aid type are then applied to the coupler target. Table 2 shows the microphone correction factors used in the Aurical. In addition, it is possible to better simulate a real ear response by measuring the patient's real ear unaided response [REUR] (Schweitzer et al, 1990) before transferring to the coupler target. If an REUR is recorded for the patient, the real ear to coupler difference [RECD] (Moodie et al, 1994) will be applied to the coupler target as well. If a patient specific REUR is not recorded, the REUR from the Knowles Electronics Manikin for Acoustic Research [KEMAR] will be applied for the RECD measurement. Table 3 shows the REUR from KEMAR that is applied when a patient-specific REUR is not recorded (Burkhard & Sachs, 1978). Within this coupler mode, the same selection of target formulas as the real ear mode is available. Thus, the loudness scaling targets can be transferred into the coupler mode to obtain variable targets for variable input levels in order to better fit nonlinear amplification.

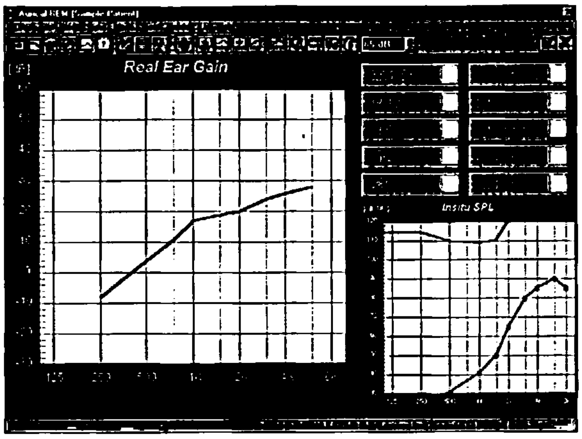

Figure 9: A real ear measurement target derived from the NAL-R formula for an 85 dB input signal.

THE AURICAL HEARING INSTRUMENT TEST MODULE

The hearing instrument test (HIT) module of Aurical allows an ANSI test to be performed with the click of a button (see Figure 10). The audiologist can choose from either the ANSI S3.22-1987 or ANSI S3.22-1996 protocol. By having both protocols available, the audiologist has the ability to use the ANSI S3.22-1996 protocol to obtain information about the acoustic properties of the hearing aid via the most current protocol, as well as being able to use the ANSI S3.22-1987 protocol to compare hearing aid test results with the specifications of the manufacturer (as most hearing instrument manufacturers publish their specifications in ANSI S3.22-1987).

As a software driven system, the Aurical allows a certain amount of customization. One way the audiologist can customize data within the HIT module is by entering the make and model of the hearing aids being tested as well as the specific test parameters of the hearing aids (i.e., automatic gain control (AGC), linear, size and type of battery, etc.) into the database. After entering this information, the hearing aids and all of their associated parameters can be efficiently selected by a few clicks of the mouse. Once entered, the make and model of the selected hearing aids will appear on the printout. Prior to entering hearing aid specific information, the audiologist can select from the default settings AGC BTE, AGC ITE, Linear BTE, and Linear ITE. Figure 11 shows the screen for selecting and entering the information concerning the hearing aids into the database.

Table 2. The microphone correction factors used within the coupler mode of the real ear measurement module. Values were derived from Libby (1986) and IEC 118-10 Appendix A (1986).

FREQUENCY IN HZ	250	500	750	1000	1500	2000	3000	4000	6000
ITE to 2cc	−3.0	−3.0	−3.0	−3.0	−1.0	1.0	3.0	−3.0	−8.0
ITC to 2cc	−3.0	−3.0	−3.0	−5.0	1.0	2.0	3.0	−1.0	−8.0
BTE to 2cc	−3.0	−3.0	−2.0	−2.0	0.0	6.0	10.0	5.0	3.0
Body to 2cc	−7.0	−7.0	−8.0	−10.0	0.0	11.0	13.0	13.0	0.0
ITE to 711	1.0	1.0	1.0	2.0	7.0	9.0	14.0	9.0	4.0
ITE to 711	1.0	1.0	1.0	0.0	9.0	10.0	14.0	11.0	4.0
BTE to 711	1.0	1.0	2.0	3.0	8.0	14.0	21.0	17.0	15.0
Body to 711	−3.0	−3.0	−4.0	−5.0	8.0	19.0	24.0	25.0	12.0

In addition to the standard protocols, the audiologist can also select the "Non-Standard" mode for testing the hearing aid within the coupler. Figure 12 shows the non-standard test screen. Within this screen the audiologist can select from various test procedures (i.e., gain, output, distortion, and battery current drain) and stimulus combinations (i.e., frequency sweep, Fast Fourier Transformation [FFT], input/output function, or a single point test). When FFT is selected it provides an ongoing spectral representation of the signal by sampling and analyzing the frequency and amplitude content of the signal at short intervals. The FFT stimulus can be selected as either white noise, with essentially equal intensity across the frequency spectrum, or speech weighted noise, with the intensity of the signal tapering off above 1000 Hz (Figure 13). When testing the hearing aid using FFT, the intensity level selected does not represent the intensity level presented at each frequency, but is the total intensity level of the signal spread across the frequency spectrum. For exam-

Table 3. REUR values recorded in KEMAR (Burkhard & Sachs, 1978).

FREQUENCY IN HZ	KEMAR REUR
200	1.0
250	1.0
315	1.0
400	1.5
500	2.5
630	3.0
800	3.5
1000	4.0
1250	4.0
1500	2.5
1600	3.5
2000	12.0
2500	18.5
3200	17.5
4000	12.3
5000	10.0
6300	5.0
8000	0.0

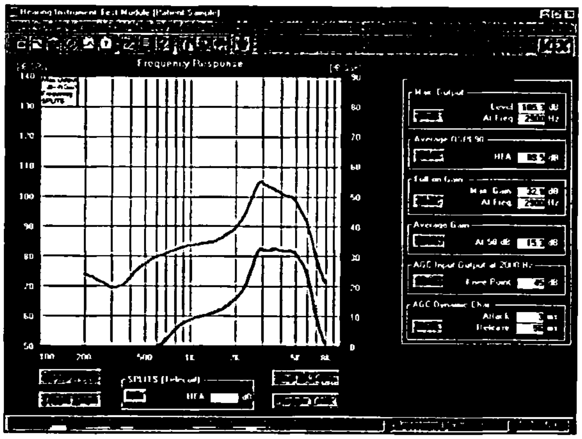

Figure 10: The hearing instrument test screen for conducting an ANSI S3.22-1996 test.

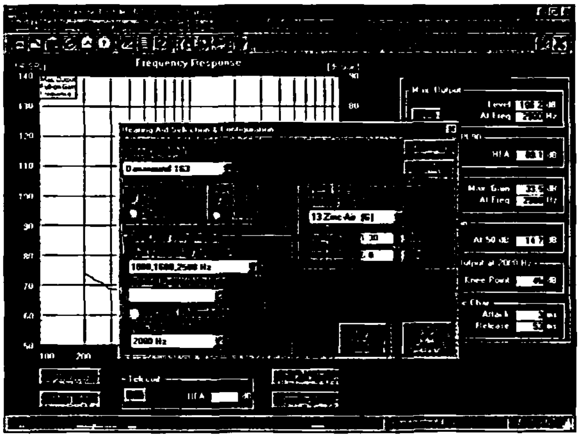

Figure 11: The hearing aid selection and configuration screen of the hearing instrument test module in the Aurical.

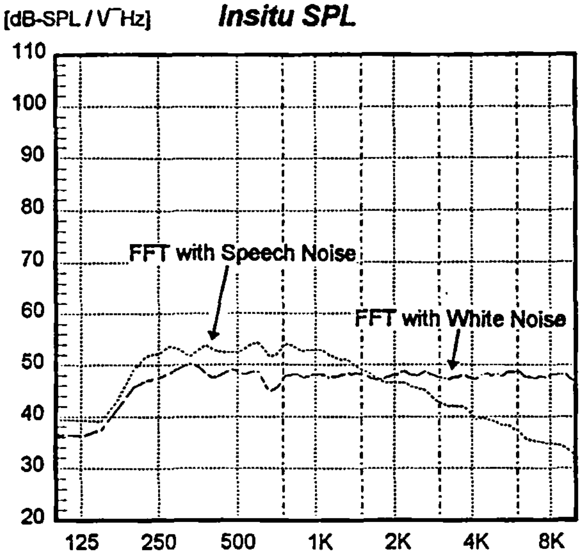

Figure 13: Examples of Speech noise and White noise in the FFT mode of the Aurical.

ple, in Figure 13, the total output level of the FFT stimulus is 80 dB SPL, however, the peak output is approximately 55 dB SPL. This stimulus, which spreads the acoustic energy across the frequency spectrum, is used to better represent environmental sounds. The flexibility available in the nonstandard mode of the hearing instrument test module will allow the audiologist to gain important information, such as the nonlinear functionality of the hearing aids in a coupler.

ADDITIONAL FEATURES OF THE AURICAL

As a NOAH™ compatible system, the Aurical is intimately connected with the NOAH compatible fitting modules. Through NOAH, data is transferred into the fitting modules as easily as it is transferred between Aurical modules, so no reentering of information is required. To make the process of programming hearing aids even more efficient, the Aurical has a HI-PRO programming box built into the Aurical itself. The programming cables of the NOAH compatible hearing instrument manufacturers plug into the top of the Aurical and are therefore always within working distance of the real ear measurement system.

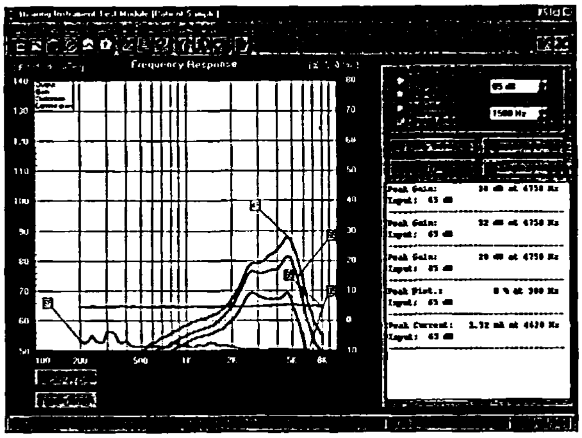

Figure 12: The hearing instrument test screen for conducting non-standard tests.

In addition to the fitting modules, the Aurical is able to communicate with other NOAH compatible features, such as office management software. Office management programs which are designed to communicate with NOAH, such as Madsen's Hearing Clinic, can add yet another step toward a totally automated audiology clinic.

FUTURE DEVELOPMENTS

As a software based system, the Aurical is continuously being updated and upgraded through the development of new software. Some of the updates that will be implemented in the future include: DSL and FIG6 as fitting formula options in the real ear measurement module, the addition of tympanometry and/or video otoscopy as a part of the Aurical system, and the ability to simulate free field testing under earphones. As these additions are incorporated into the Aurical system, existing Aurical users will be able to upgrade their Aurical units in an efficient and cost effective manner.

CONCLUSION

The Madsen Aurical incorporates multiple types of equipment and features: traditional audiometry, SPL audiometry, automated loudness scaling, real ear measurement, a hearing instrument test box, and a built-in HI-PRO box for programming hearing aids. Combining all of these abilities into the Aurical, both physically and through the software that drives them, helps audiologists to develop more efficient and effective clinical practices.

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